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Review of methods for flow velocity measurement in wind tunnels

Slavica Ristić, PhD (Eng)[1)]
Jovan Isaković, PhD (Eng)[1)]
Biljana Ilić, BSc (Eng)[1)]
Goran Ocokoljić, BSc (Eng)[1)]

Testing flow quality in wind tunnels, a highly significant activity in the field of experimental aerodynamics, includes a range of different methods and application of modern equipment. In this paper, the review of the most significant methods for subsonic and supersonic flow velocity measurement in the test sections of the wind tunnels is given. Apart from the basic principles and corresponding equipment, each method is illustrated by the results available in the references or obtained in the VTI aerodynamic laboratories.

Key words: **experimental aerodynamics, flow velocity, velocity measurement, pressure measurement, measuring methods, wind tunnel.**

Introduction

WIND tunnels are installations whose primary purpose is experimental investigation of aerodynamic characteristics for different models. They are based on the principle of relative movement - contrary to the real situation, model is still, and air is circulating. In the wind tunnels, the models or parts of aerodynamic and non-aerodynamic objects can be tested.

Velocity is one of the most important parameters of the flow quality. Uniform velocity field in the test section and accurate velocity measurement are critical for obtaining high-quality results in the wind tunnel tests. The review of methods for flow velocity measurement, which is presented here, is based on long-standing experience and available references [1-30].

First group of methods for flow velocity measurement is based on pressure measurement. In many wind tunnel tests, mean velocity in the test section is determined indirectly, by measuring stagnation and static pressures. One or several pressure probes can be used in these measurements. Velocity field in the wind tunnel test section can be determined based on the measurement of pressure distribution. Pressure probes and appropriate scanning devices can be used for that purpose.

Second important group consists of anemometry methods: Laser Doppler anemometry, hot wire and hot film anemometry, acoustic anemometry, anemometry based on particle image velocity, etc. These methods are based on direct measurement of flow velocity and formation of velocity vector field.

Optic methods for flow visualization (Schlieren, holography and holographic interferometry) can also be used in flow quality investigation, for indirect determination of flow velocity.

Determination of flow velocity in wind tunnel test section using metods for pressure measurement

There are many different methods for measuring of flow velocity in liquid and gaseous fluids. The combination of probes and transducers for measurement of stagnation and static pressure is primarily used in aerodynamic tests [1-8]. Generally, velocity of the subsonic flow is measured in two ways:

- Measurement of total and static pressure;
- Measurement of static pressure in two different cross sections of the collector.

Determination of flow velocity using measurement of stagnation and static pressures

Aerodynamic forces and moments are usually calculated using the mean value of velocity in the wind tunnel test section. Besides the need for attaining a uniform flow field, exact and simple measurement of mean flow velocity is also necessary. In the case of subsonic flow, the velocity is determined by measuring the stagnation pressure in the wind tunnel settling chamber and static pressure on wind tunnel walls simultaneously. Generally, the relation between the mean velocity and stagnation and static pressures is as follows:

$$V=\sqrt{\frac{2(p_t-p_{st})}{\rho_{st}}} \tag{1}$$

The combination of probes and elastic transducers is usually used for measuring pressures in wind tunnels. The probe, which is placed in the airflow, brings pressure to the elastic transducer, which transforms the deformation into electric signal.

Pitot probe is usually used for measuring the stagnation

[1)] Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA pressure. The Pitot probe is a cylindrical tube with a front hole, and it is parallel to the flow. Measurement error is very small, approximately 0.2% up to $M = 1$, because the performed flow stop is very quick and the influence of friction can be ignored. The shape of the tube has no influence on the measurement accuracy. Shapes used for the nose of the Pitot probes are shown in Fig.1. Ranges of the angle of attack for which the measurement error is up to 1% are also shown.

Pitot-static probe of Prandtl type is a combination of the Pitot tube and static pressure tapping, and it is used for simultaneous measurement of stagnation and static pressures. It has an open-ended hemispherical nose and a certain number of orifices on the side of the head at some distance from the nose. The appearance of Pitot-Prandtl probe is also shown in Fig.1.

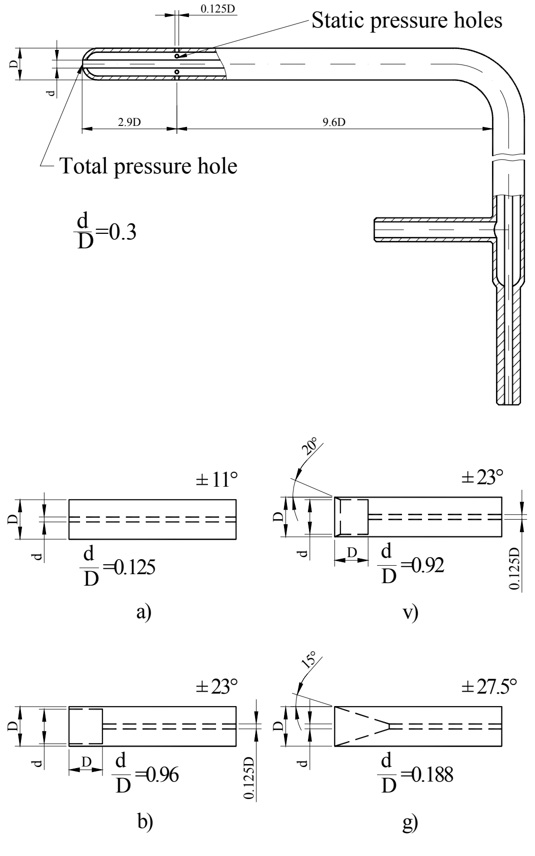


Figure 1. The appearance of Pitot-Prandtl probe and several different shapes of the Pitot probe nose

In practice, transducers based on elastic deformations of thin metal elements are used, especially for dynamic measurement. Elastic element can directly move the mechanism with the pressure indicator. However, many precise instruments transform deformation into electric signals using the electric sensor of movement. Many different types of elastic transducers are in practical use, e.g., different types of Bourdon's tubes, membranes, hollow thin cylinders, etc. These transducers measure both low and high pressures.

Natural frequencies of some elastic transducers can be up to tens of kHz, making them suitable for dynamic measurement of pressure changes. A bad feature of many elastic transducers is the failure to withstand loads higher than the permitted limit, which causes lasting damages.

Elastic transducers that are most frequently used for pressure measurement are Bourdon's tubes. The basic type of Bourdon's tube is shown in Fig.2 [8]. Increased sensitivity of the Bourdon's tube is attained by increasing the angle of torsion *Φ* (Fig.2.), so the tube obtains helical, spiral or twisted shapes. The angle of torsion can be 1 – 10 full revolutions. The sensitivity also depends on the tube thickness, the tube curve radius and Young's coefficient of elasticity. The materials that are used must have lower losses, more exactly, lower mechanical hysteresis. The elastic characteristics of Burdon's tube cause mechanical oscillation, the challenges of vibrations or shocks. In some cases oscillations are absorbed by the silicon oil. For extra precise measurements, manometers with helical Burdon's tube type made of quartz glass are used (Fig.2). Quartz is a material with the best elastic features due to the irrelevant mechanical hysteresis, and minimum losses caused by internal friction.

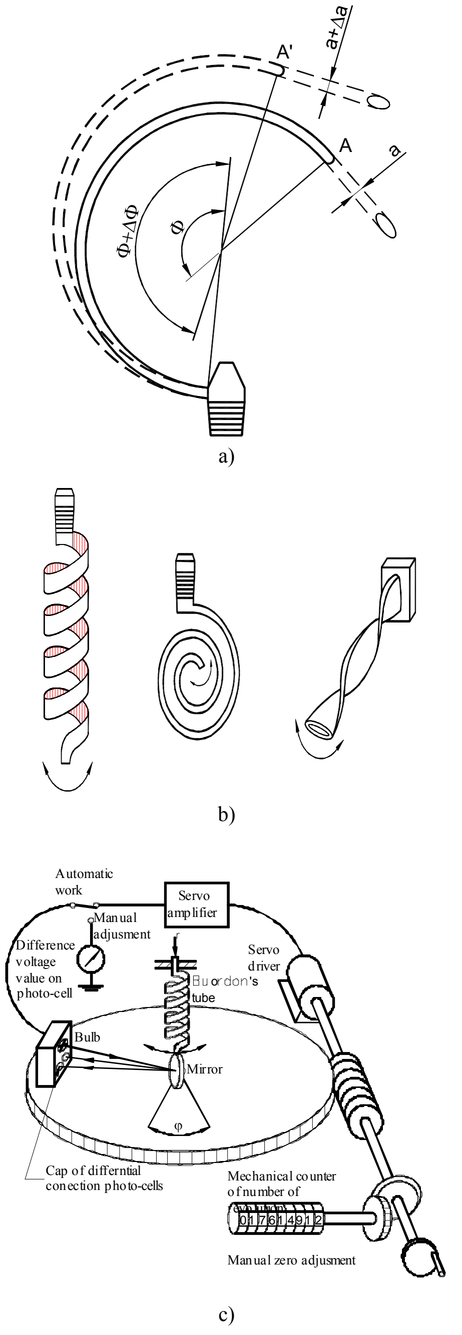


Figure 2. a) Bourdon's tube of type "C", b) some shapes of Bourdon's tube, and c) manometer with helical Bourdon's tube, made of quartz glass

The quartz is warmed up to approximately 2000 K, changing its condition to amorphous. The melted quartz has a very small coefficient of temperature spreading, $0.55 \cdot 10^{-6}$

K^{-1}. This coefficient is 20-30 times smaller than the coefficient of the majority of metals. Quartz is highly resistant to the influence of corrosive liquids and gases, and slowly growing old.

Transducers based on membrane are used in a wide range pressures up to 10^8 Pa. The force appearing due to the difference of pressures on either side of the membrane is equalized with elastic forces in the membrane. They cause movement proportionate to the pressures. Generally, this movement is a non-linear function of pressure. However, transducers are only used in the range of non-linearity of movement smaller than the define border, usually 1–5 %.

All the transducers based on membrane can be adapted for measuring the difference between the unknown and atmospheric pressures, or more exactly, unknown and some reference pressures. Vacuum is used as reference pressure for measuring very low-level pressure. Increase of sensitivity and output movement is obtained when wrinkled membranes are used. Changing of fat membrane deformations in the electrical signal are performed using glued strain gauges. Near the centre on the side of the smaller pressure deformations are positive, but in the holder vicinity deformations are negative. The membrane has two normal components of strain: radial strain and strain into tangent line direction. Places with different deformation signs exist on the membrane. This is used for glued strain gauges, which create four active branches.

Measuring of air stream velocity by two static pressures

Using the Bernoulli's equation and the law of continuity, under conditions of adiabatic changes, the velocity V, at cross section “2” (Fig.3) may be written as (2) [1, 5, 6].

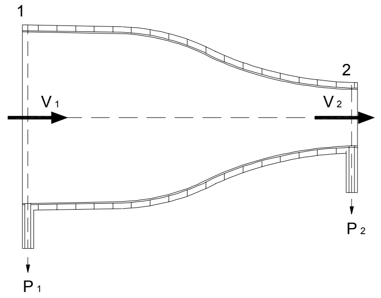


Figure 3. The cross section position for measuring static pressure

$$V_2=\left\{\frac{2\cdot\kappa\cdot P_1}{(\kappa-1)\cdot\rho_1}\left[1-\frac{P_2\cdot\rho_1}{P_1\cdot\rho_2}\left(1-\left(\frac{\rho_2\cdot A_2}{\rho_1\cdot A_1}\right)^2\right)^{-1}\right]\right\}^{\frac{1}{2}} \qquad (2)$$

In eq.(2):

$$\kappa=\frac{C_p}{C_v},$$

C_p is the specific heat at constant pressure, C_v specific heat at constant volume, p pressure, ρ air density, A cross section area.

Including the velocity of sound c, temperature T in cross section “1”, the difference of pressures $\Delta P=P_1-P_2$, the assumption that $T_1=T_0$, $P_1=P_0$, $A_2<<A_1$, can be written (4):

$$c_1^{\,2}=\frac{\kappa\cdot P_1}{\rho_1} \qquad (3)$$

$$V_2=\left\{\frac{2\cdot\kappa\cdot R\cdot T_0}{(\kappa-1)}\left[1-\left(1-\frac{\Delta P}{P_0}\right)^{\frac{\kappa}{\kappa-1}}\right]\right\}^{\frac{1}{2}} \qquad (4)$$

This method gives most accurate results for the value of ratio $\Delta P/P_0$=0.15 - 0.2. If the pressure ratio is in the range $\Delta P/P_0$=0.02 - 0.03 and it is related to the circular tube type velocity then (5) applies.

$$V_2=\left\{\frac{2\Delta P}{\rho}\left(1-\frac{A_2^2}{A_1^2}\right)^{-1}\right\}^{\frac{1}{2}} \qquad (5)$$

This equation is valid only in the case of uncompressible flow.

Measurement of flow velocity using mechanical revolution blades

For measuring airstream velocity in this way, instruments with wings and some different types of anemometers with wings are used. The hydrometric wings are often used for measuring water velocity in rivers, irrigation canals and pipelines. Rotary cycle is realized with blades that have spiral area shape. The number of cycle revolutions is caused by airstream velocity, and is measured by electrical connections. Calibration curve is straight, except at small velocities where it has parabola shape because of the influence of the boundary layer. Calibration is examined before and after measuring. The measuring accuracy is ± 2% at airstream velocity value.

Anemometers with wings operate like hydrometric wing. They are used for measuring flow velocity in wind tunnels. Most famous anemometer with wings is Woltman-cycle, where the rotation velocity of the cycle is equal to the flow velocity through the cycle.

This kind of anemometer is used for measuring flow velocity from 0.1 up to 10 m/s. For bigger velocities, anemometer with spoon (Fig.4) is used. This anemometer measures velocity in normal plane axes. They are very sensitive to the turbulence flow, and can be successfully used only in the open flow. Calibration is examined in the wind tunnels with diameter bigger than 800mm. Instruments for measuring velocity mechanically, measure only the middle value, and they are used in large cross sections.

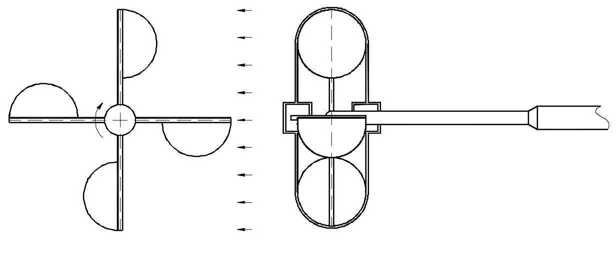


Figure 4. Anemometer with spoons

Measurement of the profile of velocity in the boundary layer

Velocity in the boundary layer can be determined based on the measurement of total pressure by specially designed probe and static pressure on the walls. Probe is moved in the boundary layer until the stabilized dynamic pressure is attained. The value of the stabilized dynamical pressure is actually dynamic pressure of the free flow [5-7].

As an example of determination of the thickness of the boundary layer, the measurement in the VTI subsonic wind tunnel T-35 on specially designed ground plane is shown. Tests are performed with opened fissure, with closed fissure, and closed or opened only at the front and rear parts. The efficiency of fissure in reducing the thickness of the boundary layer can be seen. In case of ground plane in a turbulent flow, velocity changes are given by empirical equation:

$$\frac{v}{v_\delta} = \left(\frac{y}{\delta}\right)^{1/7} \tag{6}$$

Where: v_δ - velocity on border of the boundary layer, δ - thickness of the boundary layer, y - Decart coordinate.

Curves obtained experimentally as function of distance from the ground plane are shown in Fig.5.

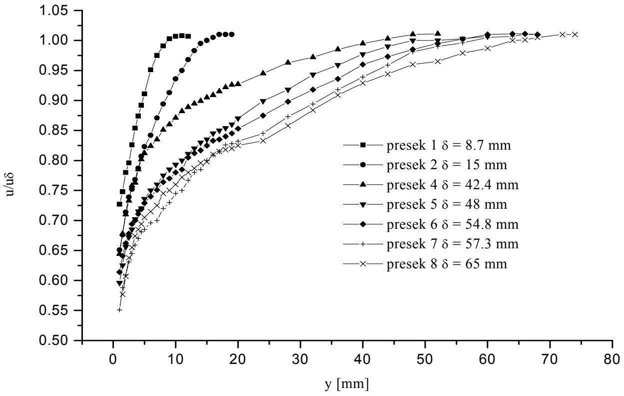


Figure 5. Velocity profile in the boundary layer for different cross sections along ground plane area

Anemometry methods

Laser Doppler anemometry

Laser-**D**oppler **A**nemometry (**LDA**) is non-contact optical method for measuring the fluid velocity, distribution of velocity and level of turbulence. Main advantages of Laser Doppler anemometry methods are [9-13, 16-18]:

- Non-contact – without flow disturbances
- Very small probe (Intersection of laser beams or only one beam) and simple selection and changing of the measured volume, which provide high resolution.
- Calibration is not required because calibration constants are defined with light wavelength and intersection angle of the laser beams (system adjustment can be checked by calibration rotating disc).

Disadvantages of LDA methods for measuring the flow velocity at wind tunnels are [9-13]:

- Optical visibility of the flow is required i.e. part of the wind tunnel wall must be visible.
- Suitable configuration of the wind tunnel and test section are required.
- Dirty wind tunnel windows or airflow itself can produce high level of noise and after signal reduction can be registered as dummy high turbulence level.
- The homogeneity, damages and stresses of glass window, may produce light refraction and dislocation within the measured volume, which must be taken into account during fluid velocity measurement.

LDA can be used for testing of: translation and rotation of objects with different dimensions and shapes, flow in different tube diameters (from few microns up to few meters), testing of air flow in the wind tunnels with speed regimes from subsonic up to hypersonic, complex flow around aircraft and missile, real flight testing, nozzle testing, river flow, propeller air flow, heat exchanger, coolers, astronomy and meteorology measurements as well as in ecological research, biological flow (blood flow) etc.

The short review of basic principles and definition

If a moving body is illuminated by light with well-known frequency, this light will be scattered within the measured volume. The distribution of the scattered light intensity is complex and depends on the incident light intensity, incidence direction, polarization plane of incident light, wavelength and characteristics of seeding particles (dimension, shape, refractive index of particles) [16-18]. Difference in frequency of the scattered and incident lights is called Doppler frequency (f_d). Doppler frequency is proportional to the velocity of the seeding particles.

Fluid velocity (with the assumption that the seeding particles have the same velocity as the air flow) can be calculated from the following equation:

$$V = Cf_d \tag{7}$$

Constant C depends on the optical characteristics of the anemometer system (focus length of optics and the angle between the laser beams θ, λ wavelength of light) and can be expressed by equation:

$$C = \frac{\lambda}{2\sin\theta/2} \tag{8}$$

LDA systems present state-of-the-art devices of the high technology equipment. Values of the velocities measured using this method can serve as etalon measurements for other measurement systems. They consist of several subsystems such as: light source (laser), optical module for guiding the laser light, transmitting and receiving the signal, data acquisition system, data reduction and presentation system, traversing system for automatic change of the measured volume and seeding generator which generates particles for light scattering and inserts them into the measured volume.

Two types of anemometers are commonly used: first with reference beam and second with interference fringes. The basic components of one-component, interference, (1D) LDA systems and measuring volume are shown in Fig. 6. At measurement point of one-component LDA two laser beams come from one source and form systems of interference fringes. Fluid particles, marker or object passing through these fringes, scatter the light with Doppler frequency f_d. Number and dimensions of the interference fringes depend on the optical and geometrical system characteristics. The measured velocity component is perpendicular to interference lines. At one point it is possible to set up two or three independent systems of interference fringes and provide simultaneous measurement of two or three fluid velocity components. Systems can be divided according to the detector position as systems in forward and systems in back scattering mode. According to the light source, LDA systems can be classified as LDA with He-Ne, Ar-ion, continual or impulse and automatic or non-automatic systems. According to optics, they can be classified into systems with classical optics and systems with fibre optics.

Fig.7a,b,c present optical modules of classical and fibre systems as well as data reduction systems [27]. He-Ne lasers with power up to 50 mW and $\lambda = 633$ nm can be used for measuring the lower speed (up to 300 m/s), Ar-ion lasers for measuring the higher speed (up to 2000 m/s). Three-component LDA systems represent a combination of one and two component systems which form three systems of interference lines in the measured volume with the combination of three different wave lengths in the laser emission spectra.(λ = 514, 488 i 476 nm). Conventional LDA systems mostly use an interference mode, while reference mode is used in the Laser Doppler Vibrometre (LDV).

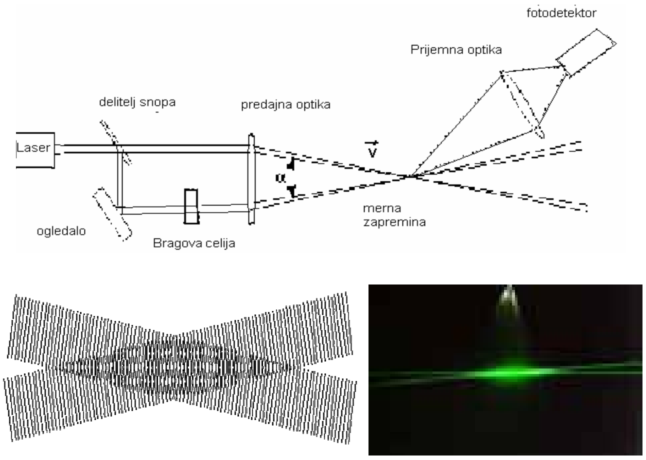


Figure 6. One-component LDA system

Basic part of the acquisition system is the photomultiplier tube, which converts light signals into current pulses. Nowadays, three systems for primary data reduction are used worldwide: tracker, counter and burst analyzers. The third system unites positive characteristics of the tracker and counter and is built into contemporaneous anemometers. They are fully computerized with the frequency range of up to 100 MHz. Data reduction is done via computer. The obtained results are presented in the form of histograms or vector diagrams (Fig.7) [9-13].

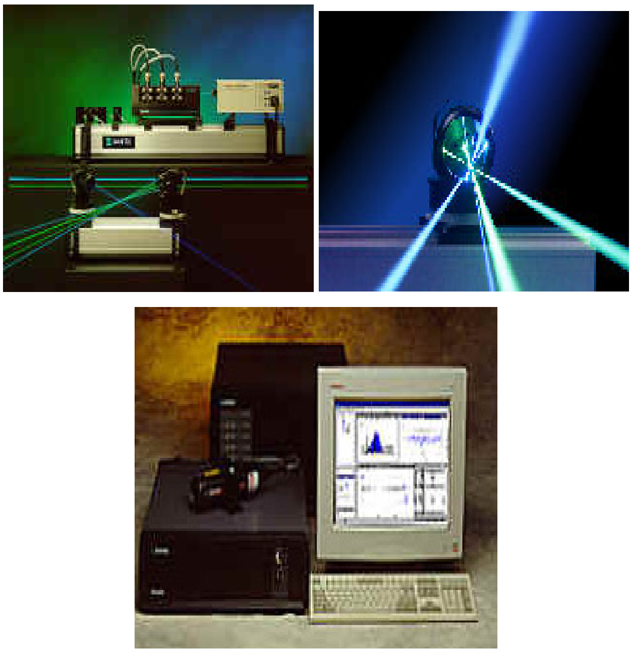


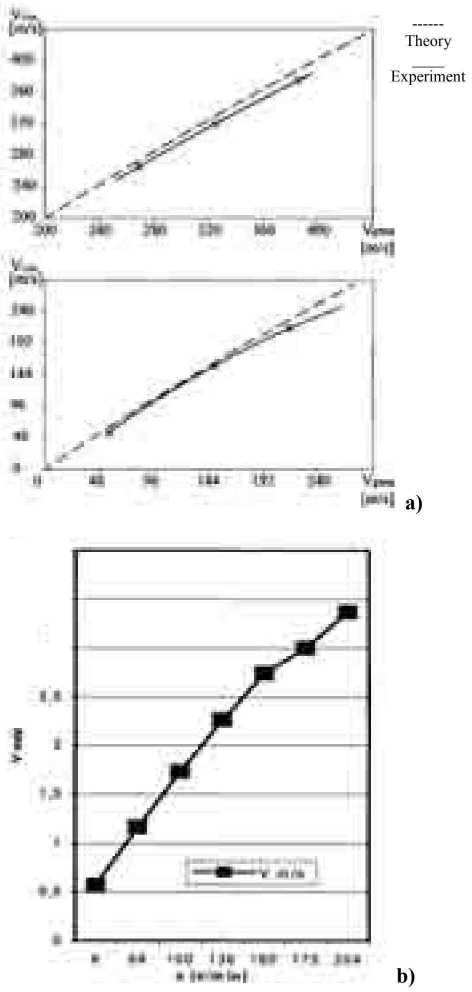
Figure 7. LDA systems with classical (a) and fiber optics (b) and system for data acquisition, reduction and results presentation (c)

Contemporary LDA have systems for automatic change of the measured volume on the programmed trajectories. They have traversing velocity of 100mm/s, with 0,1mm positioning accuracy. Systems with fibre optics have higher possibilities because of the lower dimension and measuring modules weight. They can be used for wind tunnel -testing as well as measuring the flow around in-flight aircraft.

For LDA, the selection of seeding particles (scattering centres) is very important as well as the quality of surface where the measuring volume is positioned [9-13]. Natural concentration of the particles in the wind tunnel air is not sufficient and it is necessary to add a controlled amount of selected particles. There are special generators for seeding particles (liquid or solid) and their injection into the measured volume. The quality of the recorded signals depends on the dimensions and physical parameters of the particles. It is shown, that it is not necessary to add particles for measuring in water.

Application of the LDA method in velocity measurements

In all well-known centres for aerodynamic investigation, the LDA method is used as the basis for measuring the flow quality. Application of LDA methods is illustrated by the results obtained during test section calibration of trisonic wind tunnel T-38 (Fig.8a), where velocity V_{LDA}, measured using LDA method and velocity $Vpms$, measured with primary measuring system (PMS) are presented.



Figur e 8. (a) Test section calibration results of the trisonic wind tunnel T-38, (b) Velocity measurement in axes of water cavitational tunnel T-33 using LDA method.

In Fig.8b calibration curve for the test section of the water cavitation tunnel T-33 is shown [9-13]. Velocity changes measured by 1D LDA system as function of the *rpm* (n) of the drive motors are also shown.

Advantages of the measurements done using the LDA method within complex aerodynamic tests are shown at the points where other methods can not provide satisfactory results because of different influences [13]. Fig.10 shows vector velocity map around the water pump vane. The pressure coefficient is defined based on these measurements. This example illustrates the advantages of the LDA methods: it does not require a specially manufactured model with orifices and can be used for measurement at all cross-sections and all transparent surroundings.

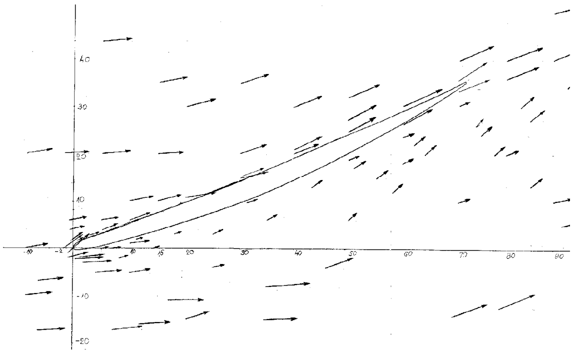


Figure 9. Velocity vector map around the pump vane profile.

Nowadays, it is not possible to imagine any significant laboratory, which investigates the flow velocity, vibrations, light scattering, particles dimensions, etc., without the LDA systems.

Hot wire and hot film anemometry

Hot wire and hot film anemometers are used for measuring the variables in the turbulent flow e.g. mean velocity components, velocity fluctuations, mean temperature, temperature fluctuations, etc. Sensors, which are thin metallic units, are placed in the flow field and warmed up by the electrical current. Heat exchange between the wire (film) and fluid depends, among other things, on the flow velocity and temperature.

The basic elements of hot wire and hot film anemometers are a probe with the appropriate sensor and electrical circuit, which brings the electrical current for warming up the sensor.

Hot wire probe

A typical probe of the hot wire anemometer is shown in Fig.10 [14]. Hot wire sensor has 0.0038 mm to 0.005 mm diameter, and length of 1 mm to 2 mm. This type of sensors is mainly used for measurement of turbulence intensity in the wind tunnels, determination of the flow field around the model and measurement in vortex trail behind the radial compressor blades.

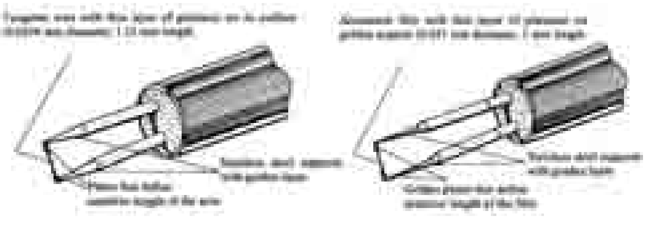


Figure. 10. Typical hot wire sensor

Hot wire sensor has two basic characteristics:

- High temperature resistance coefficient;
- Electrical resistance that enables easy warming up using the electrical current, for practically attainable levels of electrical current and voltage.

Hot wires are usually made of tungsten, platinum or alloy of platinum and iridium. Tungsten is currently the material that is the most frequently used for hot wires. Thin layer of platinum is usually applied on tungsten hot wires, in order to improve contacts with plates on the wire ends and with the wire support.

Hot film probe

Typical probe of the hot film anemometer is shown in Fig.10 [14]. In essence, hot film sensor represents a conductive film on the ceramic base, with diameter of 0.025 mm or larger in case of cylindrical shape of the film. In Fig.10, quartz support with platinum film is shown. Golden plates at the support ends are borders of the measured length and they strengthen the contact with the sensor support.

The thickness of the metallic film on the sensors of this type is very small, so strength and heat conductivity mainly depend on the characteristics of the film base. The film is usually made of platinum, because of its good oxidation resistance. Small strength of platinum is not important in this case, as platinum film is applied on the support. Thin layer of aluminium is usually applied on the film, because of its abrasion resistance and good heat conductivity.

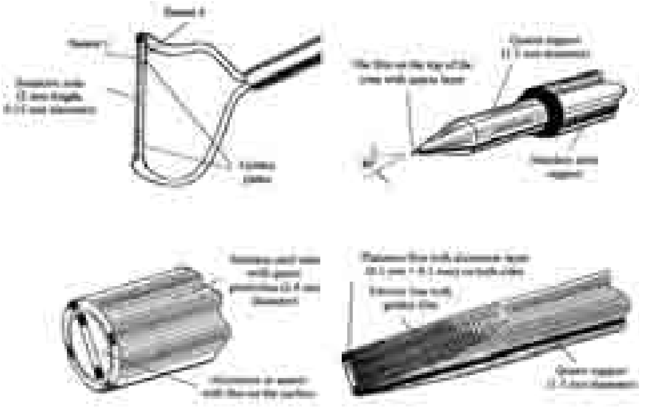


Figure 11. Some types of hot film probes: (a) Probe with separated film, (b) Cone hot film probe, (c) Pipe hot film probe, (d) Wedge hot film probe

Electrical circuit

Two basic types of electrical circuits are used with hot wire sensors – with constant electrical current and with constant temperature. In the systems with constant electrical current, frequent response of the sensor depends not only on its characteristics, but also on the heat exchange between the sensor and airflow, which is a strong limitation in the systems of this type. Knowing that sensor response depends on the changes in the airflow, there is a need to change frequent compensation of the sensor. It is not feasible in case of rapid changes of the flow parameters. Thus, anemometer with constant electrical current is the most suitable when the velocity fluctuations are small with regards to the mean velocity.

The system with constant temperature exceeds limitations of the system with the constant electrical current. Increasing airflow velocity around the sensor, its temperature is decreasing, and so is the resistance. Smaller resistance also means smaller voltage, and voltage input of amplifier is changed. The amplifier phase must lead to its output increasing, i.e. to increasing of the sensor current. Thus, electrical current increasing or decreasing immediately corrects each change of the sensor resistance.

Besides a probe with a sensor and the appropriate electrical circuit, equipment for data acquisition and reduction is also needed for measurement with hot wire and hot film anemometers. Some typical elements of this equipment, which are in use in the wind tunnel measurements, are the following (list is not exhausted): RMS voltmeters, filters for output signal, output signal amplifiers, correlators, spectral analysers, data acquisition systems, data reduction systems.

Determination of the flow velocity

The method for determining the velocity using pressure measurements is limited to the cases of the stationary flow. The problem is the time delay of the pressure in the probe, contacts and manometer. Resonant oscillations of gas or liquid in the probe and in the measuring equipment can thoroughly disable the measuring. The method of measuring velocity using pressures measurement, i.e. measurement of stagnation and static pressures, can only be applied for the frequencies of up to several Hz.

Hot wire anemometers give the best results for both stationary and non-stationary flows. They enable measurement of velocity of gases and liquids, starting from the range of stationary velocities, and up to very rapid changes, with frequencies of several kHz. Because of very small dimensions of the probes, measurements are actually performed in a point.

The range of possible applications of hot wire anemometers is expanded, so it now also includes the following: measurement of velocity in the cases when the Pitot probe is too large, measurement of temperature and changes of temperature, flow investigation at temperatures up to 600 ºC, acoustic measurements, vortices investigation (Karman's vortex trail), boundary layer measurements, laminar to turbulent flow transition, investigation of compressible shock waves, measurement of flow angularity changes, investigation of the supersonic flow in jet engines, etc.

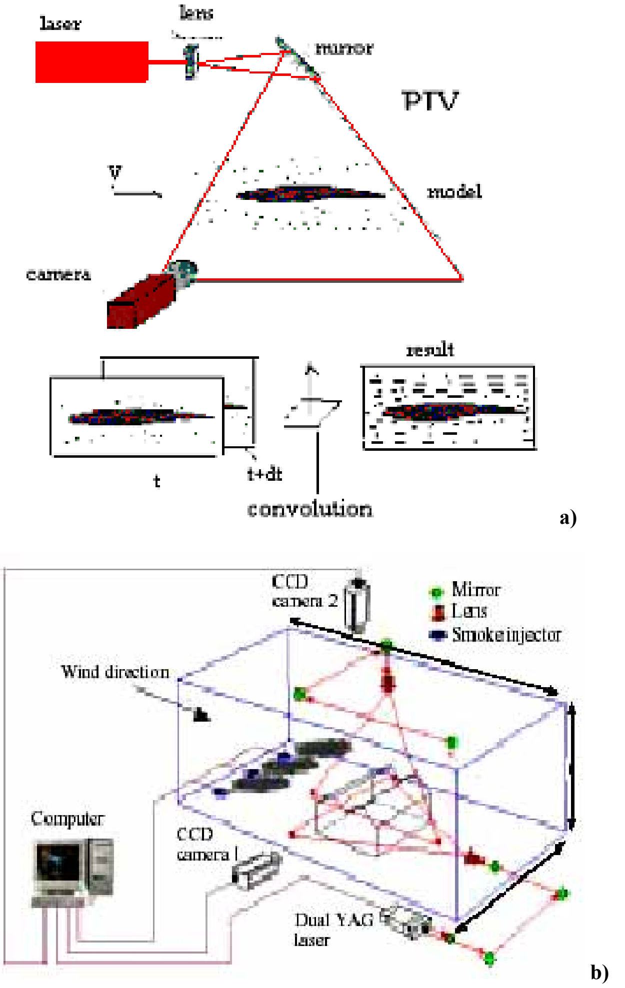
Particle image velocity

Particle Image Velocimetry (PIV) is an important experimental tool for fluid mechanics and aerodynamics. The basic principle involves photographical recording of the motion of microscopic particles that follow the fluid flow [15, 16, 18, 19, 25]. PIV allows the velocity of a particle in the fluid to be simultaneously measured throughout a region illuminated by a two-dimensional laser light sheet. PIV is non-intrusive and therefore the measurements obtained are free from disturbance and thus highly accurate. The technique is ideal for unsteady aerodynamic flows.

The positions of the particles are recorded on either photographic film or digital CCD cameras at each instant the light sheet is pulsed t i $t+\Delta t$. Fig.12. shows the fundamental principles of PIV (a) and schematic diagram of the test section of the wind tunnel including the PIV system (b).

The data processing consists of either determining the average displacement of the particles over a small interrogation region in the image or individual particle displacement between pulses of the light sheet. Knowledge of the time interval between light sheet pulses then permits computation of the flow velocity. The PIV technique may be classified as:

- 2D PIV, used when the flow velocity vector has two components in the plane normal to the camera axis
- 3D stereoscopic PIV, uses two simultaneous cameras positioned on the stereoscopic angle. The 3D velocity vector can be determined from pairs of photo-records [15].
- PIV for volume mapping or, holographic PIV (HPIV) is the technique for recording 3D images of particles and 3D distribution of the flow velocity vectors [15].
- PIV for two-phase flow.
- PIV for microflow with dimensions lower than 300μm. The seeding particles have up to 200nm diameter.
- PIV for combinated measurements of velocity, concentration and temperature.



a)

b)

Figure 12. Fundamental principles of PIV (a) and schematic diagram of the test section of the wind tunnel including PIV system (b)

Particle Image Velocimetry (PIV) is increasingly used for aerodynamic research and development [15]. The PIV technique allows recording of the complete flow velocity field in a plane of the flow within a few microseconds. Thus, it provides information about unsteady flow fields, which is difficult to obtain using other experimental techniques. The short acquisition time and fast availability of data reduce the operational time, and hence cost, in large scale test facilities.

A pair of pulsed Nd:YAG lasers with frequency of 10Hz and pulse separation of some μs, are used to provide the pulsed light sheet illumination in the PIV experiments. The position of particles entrained in the flow is recorded by a

CCD camera, which is oriented 90 degrees to the plane of the light sheet. Image processing is made with software intended for this specific purpose. Fig.12 shows the PIV set up. Fig.13 shows: velocity measured around the pressure measurement probe (a), wing of airplane Boeing (b) [19].

Depending on the type of CCD camera used and the particle concentration, either particle tracking or correlation processing can be used to produce the processed velocity vector map. In some instances, particle tracking can be used after correlation processing to provide "super resolution" particle velocity maps.

Sometimes, the combination of classical PIV and holography is used for measuring the velocity vector in the wind tunnel test section. Holographic Particle Image Velocimetry (HPIV) is a compilation technique between PIV and holography, that measures the instantaneous three-dimensional (3D) velocity of fluid flows in a volume using holography [15, 25].

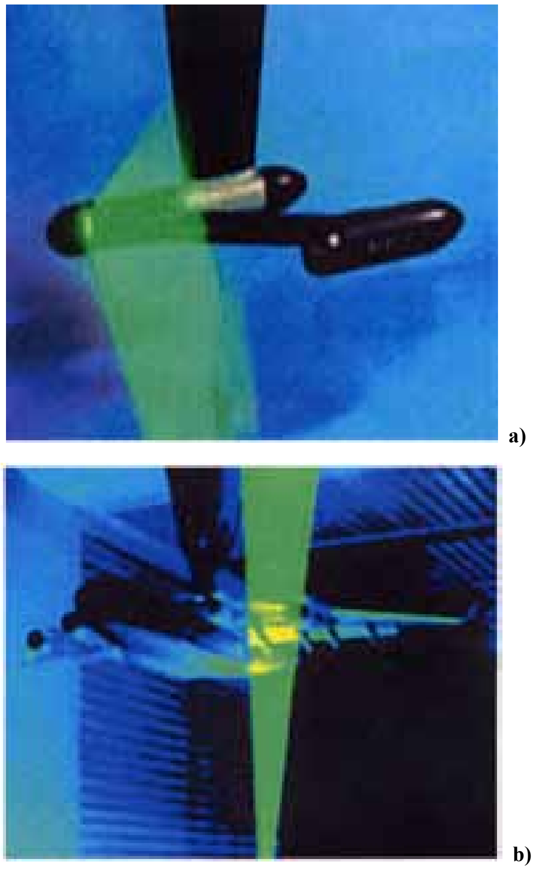


Figure 13. Measurements of the velocity vector by PIV

The 3D information of natural or seeded particles in the flow is recorded on a hologram instantaneously using two or more short laser pulses. The reconstructed 3D-image field contains information about the 3D positions, size and shape of the particles (Fig.14). By finding the 3D displacements of particles in the image volume between two exposures separated by a short time lapse, an instantaneous, volumetric 3D velocity field can be retrieved. HPIV can measure velocities with accuracy within a few percent and spatial resolution ~1mm. These methods are used for a wide range of velocity and for simultaneous determination of histogram, path and particle velocities. The beginnings of these methods can be traced back to the early 1980s.

The HPIV process consists of three steps: recording the hologram, reconstructing the object field from the recording, and analysing the reconstructed field. During recording, ‘object’ wave (light scattered from the particles) is combined on a holographic plate with a reference wave (unscattered) to produce an optical interference patterns. During reconstruction, the re-introduction of the reference wave on the hologram reconstructs the object wave in the 3D space. The reconstructed 3D image can then be analysed, scanning it with a video camera, in order to retrieve particle information. Determination of particle velocity can be made in two ways: the image of the particles recorded on the interferograms, and their displacements, can be identified by high resolution cameras or analysis of diffraction effects displacements on the holographic plates recorded consecutively.

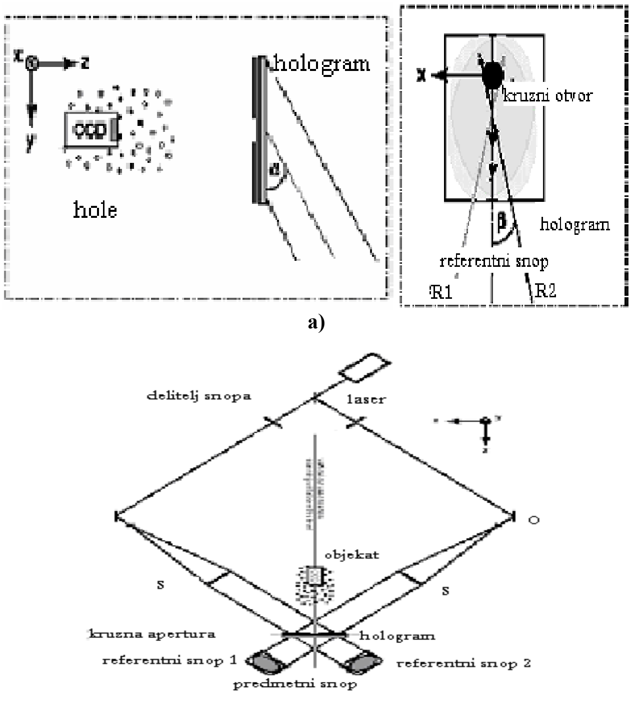


Figure 14. Holographic Particle Image Velocimetry (HPIV)

Yet, holography systems are not produced in a commercially available form due to the complexity and variety of the systems needed for different applications. Customized designs are usually tailored to specific applications.

Table 1. Comparison of velocity measuring systems advantages and disadvantages

System / Criteria	Hot Film Probe (HWA)	Laser Doppler anemometry (LDA)	Particle ImageVelocimetry (PIV)
Intrusiveness	Intrusive	Non-intrusive	Non-intrusive
Availability commercially	Available	Available not commercial	Available for real time use
Price	Relatively inexpensive	Very expensive	Moderately expensive
Real-time capability	Yes	Yes	Not commercially available
Separate velocity components	Only combination of U and V (magnitude)	Up to 3 independent velocity components	Up to 3 independent celocity components
Frequency response	Excellent	Good	Limited by camera / caser
Ease of calibration and positioning	Difficult to calibrate in water	No calibration necessary	Easy to calibrate
Multi sensor capability	One sensor location per probe	One sensor location per unit	Numerous sensor locations

Numerous methods are cited in the references for fluid velocity measurements. Some methods use ions or luminescent particles as seeding, acoustical Machmeters, or anemometers with electrical discharge [16, 18]. Table 1 shows the comparative analysis of the main characteristics of the methods of anemometry.

Determination of the flow velocity by optical methods

Flow visualization is an important tool of experimental aerodynamics, which renders certain properties of a homogenous flow around the model testing in the wind tunnels accessible to visual perception and recording [6-18, 20-25].

The visualization techniques have been extensively expanded during the past decades, in the sense of development and application of new methods in the wind tunnel flow quality testing. The fundamental classification of the flow visualization methods is:

1. techniques which use a foreign material, added to the flow, with the same mechanical characteristics as the flow, but with different optical features,
2. optical methods
3. special methods that are somehow a combination of the two above mentioned methods

The most important flow visualization methods for a wide range of velocities are the optical ones. They make possible obtaining qualitative and quantitative information about the flow. All optical methods are based on recording the density changes caused by aerodynamic effects, and their influence on the optical beams passing through the tested flow. The light beams carry out the flow density changes as modulation of amplitude, phase and beam propagation [16-18, 20-25]. The three principal optical methods for flow visualization are:

1. shadow,
2. Schlieren and
3. interferometry.

Holographic interferometry is the most important and most powerful optical method.

Schlieren method

Schlieren method can be wind tunnel velocity calibration method, when used with test models as cone, sphere, projectile or airplane models, mounted in test section with compressible flow.

The appearance of Schlieren effects and their location give the information about Mach number, i.e. flow velocity, symmetry, flow angularity, density gradient in the whole test section and etc.

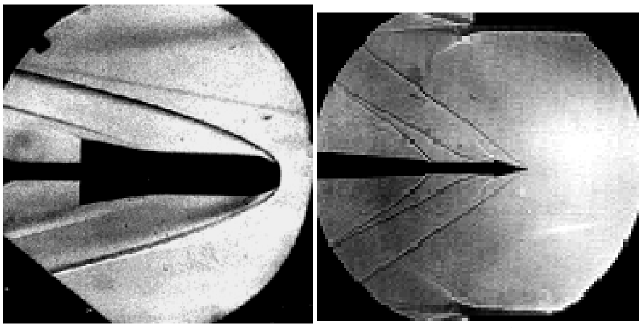

a) b)

Figure 15. Schlieren effects around the cone in the wind tunnel T-34 for $M_\infty = 7$, and in hypersonic wind tunnel T-36 for $M_\infty = 1.55$.

Fig.15 shows the Schlieren effects around the cones in the wind tunnels T-36 and T-34. The Mach number in the test section is precisely calculated from these Figures (16-18, 24 and 30). Analytical method of Billig's empirical equation proves that Mach number in the free flow (Fig.15a) is $M_\infty = 7$ [24].

The value of the top shock wave angle (Fig.15b) is the bases for Mach number determination. Mach number in the free flow is $M_\infty = 1.55$. It shows that the calculated and nominal Mach numbers are very similar.

Holographic interferometry

Holography and holographic interferometry are the methods applied for non-destructive, contactless testing of different flows, processes and objects. They make possible obtaining complete three-dimensional information of the tested phenomena. It is possible to analyse the events occurring at different times. Holographic interferometry gives the 3D space properties distribution of the tested object. This method is often used for high speed aero-optic phenomena, as flow in the wind tunnels, shock pipes, plasma, combustions and etc.

The holographic interferometer, as modular type, is designed, made and tested in the VTI laboratory. Interferometer is not commercially available, it is intended for wind tunnel tests with the possibility of easy modifications which allow application of different methods: double exposure, real time, time average, multipassing object beam, multibeams interferometry, interferometry with parallel or diffuse object beam, "sandwich" method, etc.

The ruby laser (Apollo model 22, $E = 3\text{J}$, $t = 30\text{ns}$, $l_c = 2\text{m}$) (2) is used as a recording light source. The He-Ne laser: $\lambda = 633$ nm, $P = 15\text{mW}$ and $l_k = 10\text{m}$ iz applied for adjustment of interferometer, for reconstruction and recording of holographic images. The system for recording, digitalizing and processing of holographic interferogarms consists of a digital camera and standard PCTV card.

Holographic interferometry is an optical method that makes possible complete quantitative three-dimensional flow testing using only one hologram, if the tested field is two-dimensional or symmetrical. A viewing angle of 180° is theoretically necessary for the investigation of the random three-dimensional objects. The interferograms in that case are recorded with ground glass (diffuse light beams) or with separated three holograms exposed at the same time.

The optical methods are often used for establishing the Mach number M_∞, in a supersonic free stream flow, by measuring the inclination of the attached shock wave, to the direction of the undisturbed flow. The attached shock wave appears when the wedge or cone is placed at zero incidences in the supersonic flow.

When the number of interferometric fringes (N) is determined, the distribution of index of refraction n can be calculated for all the points of the object [18, 19]. Gladstone-Dale equation is the basic relation connecting the flow field, optical and other physical characteristics, density ρ and index n.

$$n(x,y,z) - 1 = K\rho(x,z,y) \tag{6}$$

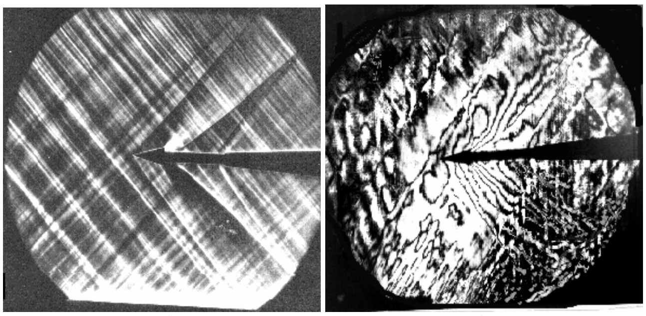
For the case of isentropic flow, the following relations are between the index of refraction n , number of fringes

N, velocity V and Mach number M and air density ρ. L is the width of the wind tunnel test section.

$$V(x_2,z_2)=2C_pT_0\left[1-\frac{\rho(x_1,z_1)}{\rho_0}\pm\frac{N\lambda}{KL\rho_0}\right]^{\kappa-1} \tag{7}$$

$$M(x_2,z_2)=\frac{2}{\kappa-1}\left\{\left[\frac{KL\rho_0}{KL\rho(x_1,z_1)\pm Nz}\right]^{\kappa-1}-1\right\} \tag{8}$$

Figures 16a and 16b show the recorded Schlieren effects and holographic interferogram of the wind tunnel T-36 test section with perforated walls and model, around the cone with top angle $\theta c=30^\circ$ for $M_\infty=1.056$. The flow perturbation (the pressure fluctuations), caused by perforations are visible on the photos [19, 25, 31]. The Mach number and the velocity of the flow are confirmed using these photos.



a) **b)**

Figure 16. Illustration of the flow testing with optical methods: (a) Schlieren and (b) holographic interferometry.

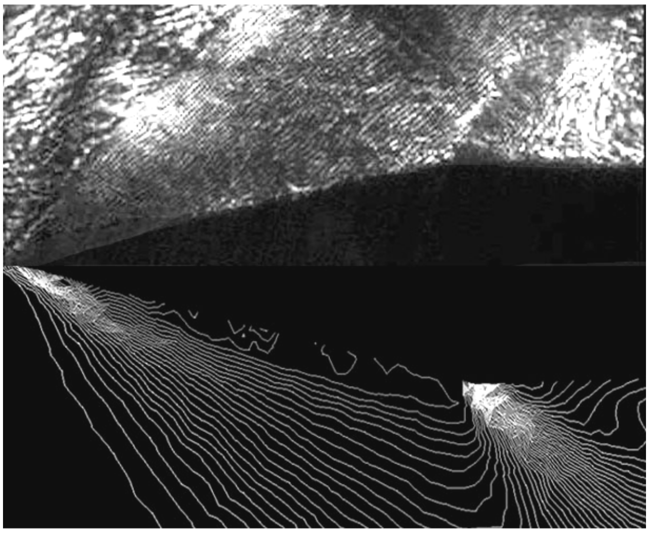


Figure 17. Isodensity line around the model cone-cylinder obtained from holographic interferograms (the above part) and numerical ones calculated by Fluent (lower part) for M_∞ = 1.476.

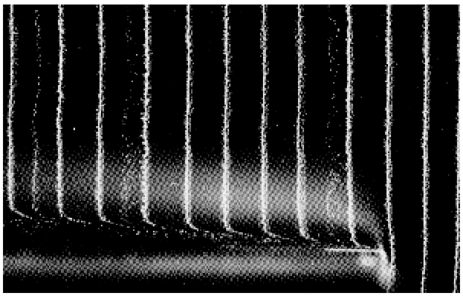


Figure 18. Hydrogen bubbles used for velocity profiles of the boundary layer over a flat plate determination

Fig.17 shows the experimental results recorded and theoretical simulated isodensity lines of symmetrical flow around the cone-cylinder model. It can be seen in the photo that the angle of the shock wave is the same $(\Theta u=45.2^\circ)$. The excellent agreement of theoretical and experimental isodensity lines is in the region between the model surface and shock wave and the region of expansion fans. The Mach number of the free flow is M_∞ =1,49. Mach number measured by primary measuring system (PMS) of the wind tunnel is ΔM_∞ = 2,6%.

The flow visualization methods which use different foreign materials as tracer particles (for example, visualization of the boundary layer over a flat plate by consecutive rows of hydrogen bubbles, Fig.18) make it possible to determine the velocity in the flow [18, 25].

Conclusion

Reliability of the results of testing of the airplane and projectile models is in direct function of the flow quality in a wind tunnel test section. Velocity is one of the most important quantities which characterize the flow quality.

Testing of flow quality in a wind tunnel test section also includes forming of the map of velocity vector distribution in the test section, in different sections, perpendicular or parallel with the test section axis, in the boundary layer, etc. Basic measurements of velocity are performed by measuring the pressure distribution.

Rapid development of contemporary technology enables the development of an increasing number of methods for measuring the flow velocity in a wind tunnel. Authors performed a substantial references survey and presented methods which are frequently used in the most distinguished centres for aeronautics and space research. For each method, basic principles, technique, description of equipment and typical results are presented, both from the VTI wind tunnels tests and cited references.

References

[1] ANDERSON,J.D.: *Fundamentals of aerodynamics*, McGraw-Hill, Inc, 1996.

[2] MICHEL,U., FROEBEL E.: *Lower limit for the velocity fluctuation level in wind tunnels*, Experiments in fluids 6, pp. 49-54, 1988, Stockholm, 2002.

[3] OWER,E., Pankhurst,R.C.: *The measurement of air flow*, Pergamon Press, 1977.

[4] MEDVED,B.: *An experimental investigation of pressure fluctuation mechanism for different transonic porous wall configuration*, AIAA 90-1417, 16th Aerodynamic Ground Testing Conference, June 16-18 1990, Seattle, Wa.

[5] POPE, A.: Wind-tunnel testing, John Wiley & Sons, Inc., New York, 1954.

[6] HOLMAN,J.P., Gajada,W.J.Jr.: *Experimental methods for engineer*s, Internal student edition, McGraw-Hill International Company, 1984.

[7] RAJAČIĆ,Z.: *Preliminarno određivanje kvaliteta struje u radnom delu "A", aerotunela T-35,* V3-2634-i-025, Vojnotehnički Institut Žarkovo, maj,1990.

[8] *Low speed wind tunnel testing*, Internal edition, Military Technical Institute of Yugoslav Army, September 1997.

[9] RISTIĆ,S., VITIĆ,A., *Baždarenje aerodinamičkog tunela pomoću 1DLDA sistema* , Scientific-Technical Review, 1989, Vol.39, No.5.

[10] RISTIĆ,S., ILIĆ,J.: *LDA measurements of the Fluid State in Different Geometries*, Transactions, 2000, No.1.

[11] RISTIĆ,S. and all.: *The Analysis of Characteristic Materials for Fluid Seeding Partiles in Wind Tunnels and Their Influence on the LDA System Functions*, Balkan Physics Letters 7 (2), 1999, pp.93-102.

[12] RISTIĆ,S.: *Bazdarenje vodenokavitacionog tunela pomocu jednokom-ponenetnog laser dopler anemometra,* V3-2669,VTI, 1991

[13] RISTIĆ,S., MAJSTOROVIC,P.: Eksperimentalno ispitivanje relativnog strujanja kroz model prave profilne rešetke, Scientific-Technical Review, 2000, Vol. 50, No.6, pp.29-36.

[14] Thermo-Systems Inc.: *Hot wire – hot film – ion anemometer systems*, 1975.

[15] KOMPENHANS,J., RAFFEL,M., DIETERLE,L., DEWHIRST,T., VOLLMERS,H., EHRENFRIED,K., WILLERT,C., PENGEL,K., KAHLER,C., SCHRODER,: *Particle Image Velocimetry in Aerodynamics: Technology and Applications in Wind Tunnels*, Journal of Visualization, 1998, Vol.2, No.3-4.

[16] RISTIĆ,S.: *Flow visualization technics in wind tunnel*, VTI, 1996.

[17] RISTIĆ,S.: *Prilog razvoju metoda vizualizacije strujanja primenom laserskih tehnika*, dok.rad, ETF, Beograd,1993.

[18] MERZKIRCH,W.F.: *Flow Visualization,* 1st ed.Academic Press, New York, 1974.

[19] National Advisory Committee for Aeronautics: *Twentieth Annual Report*, 1934.

[20] KLEINE,H., TAKAYAMA,K.: *Development of a Simultaneous Holographic Interferometrer/Color Schlieren System for the Investigation of Compresssible Flows*, 9th International Symposium on Flow Visualization, 2002.

[21] RISTIĆ,S.: *Disturbance of Transonic Wind Tunnel Flow by a Slot in the Tunnel Wall. Exper. in Fluids*, 1991, No.11, pp.403-405.

[22] RISTIĆ,S.: *Holografija i njena primena u vizualizaciji strujanja*

[23] RISTIĆ,S.: *Testing of Flow Field Around the Nozzle Edge Using the Method of Holographic Interefrometry*, Fizika, 22(3)1990, 529-543.

[24] Ristić S., Vitić A., Vučković S., Mach Number Determination of Hypersonic Flow with New Schlieren System., NTI, vol. no5/6 2002

[25] RISTIĆ,S.: *Pregled postojećih metoda vizualizacije strujanja, dosadašnja primena i perspektiva razvoja i pririmene u aerotunelim*a, VTI, 1984, V3-2269-I.

[26] RISTIĆ,S.: *Vizualizacija strujanja u aerodinamičkim tunelima*, Glasnik RV i PVO, 1990, Br.1, St.16-24.

[27] VITIĆ,A.: *Određivanja kvaliteta strujanja u nadzvučnom opsegu brzine strujanja radnog dela aerotunela T-38*, VTI, V3-2367-I, 1985.

[28] VITIĆ,A., VUKOVIĆ,Đ.: *Određivanje korekcije Mahovog broja u aerotunelu T-38 u opsegu* $1.1< M_\infty<1.4$ *korišćenjem Šliren metode i standoff modela,* V3-2364-I , VTI, 1985.

[29] VITIĆ,A.: *Istraživanje strujanja u radnom delu aerotunela T-38 metodom holografske interferometrije*, Elaborat, završni izveštaj, V3-2800-I-EA, VTI, 2003.

[30] VITIĆ,A.: *Merenja kvaliteta struje vazduha u 3DFN radnom delu aerotunela T-38 u opsegu mahovih brojeva od* $M = 0.3$ *do* $M = 0.7$ N.

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Pregled metoda merenja brzine strujanja u aerotunelima

Ispitivanje kvaliteta strujanja u aerotunelima je veoma značajna aktivnost u eksperimentalnoj aerodinamici, koja obuhvata niz različitih metoda i koristi modernu opremu. U ovom radu prikazan je pregled najznačajniih metoda koje se koriste za merenje brzine strujanja u radnom delu aerotunela za podzvučne i nadzvučne brzine. Pored osnovnih principa i pripadajuće opreme, svaka metoda je ilustrovana rezultatima dostupnim u literaturi ili dobijenim u aerodinamičkim laboratorijama VTI-a.

Ključne reči: **ekspreimentalna aerodinamika, brzina strujanja, merenje brzine, merenje pritiska, metoda merenja, aerodinamički tunel.**

Обзор и анализ методов измерения скорости потока в аэродинамических трубах

Испытывание качества потока в аэродинамических трубах очень значащая деятельность в экспериментальной аэродинамике, охватывающая диапазон различных методов и пользует современное оборудование. В настоящей работе показан обзор и анализ самых значащих методов, которые пользуются для измерения скорости потока в рабочей части аэродинамической трубы для дозвуковых и сверхзвуковых скоростей. Кроме основных принципов и подходящего оборудования, каждый метод иллюстрирован результатами имеющими в учебниках или полученными в аэродинамических лабораториях ВТИ.

Ключевые слова: экспериментальная аэродинамика, скорость потока, измерение скорости, измерение давления, метод измерения, аэродинамическая труба

Tableau des méthodes pour mesurement de la vitesse du courant dans les souffleries aérodynamiques

La recherche sur les mouvements du courant dans les souffleries aérodynamiques représente une activité importante dans le domaine de l'aérodynamique expérimentale et comprend une série de différentes méthodes en utilisant l'équipement moderne. Dans ce travail on a présenté le tableau des méthodes les plus importantes qui sont employées pour mesurer la vitesse du courant dans la chambre d'expérience de la soufflerie aérodynamique pour les vitesses subsoniques et supersoniques. Outre les principes de base et l'équipement correspondant, chaque méthode est illustrée par les résultats disponibles dans la littérature ou obtenus dans les laboratoires aérodynamiques du VTI.

***Mots clés*: aérodynamique expérimentale, vitesse du courant, mesurement de la vitesse, mesurement de la pression, méthode de mesurement, soufflerie aérodynamique.**